RIVER RESEARCH AND APPLICATIONS

River. Res. Applic. **24**: 506–518 (2008)

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/rra.1134

DETECTING BIOLOGICAL RESPONSES TO FLOW MANAGEMENT: MISSED OPPORTUNITIES; FUTURE DIRECTIONS

YVES SOUCHON,[a*] CATHERINE SABATON,[b] ROBERT DEIBEL,[c] DUDLEY REISER,[d] JEFFREY KERSHNER,[e] MARK GARD,[f] CHRISTOS KATOPODIS,[g] PAUL LEONARD,[h] N. LEROY POFF,[i] WILLIAM J. MILLER[j] and BERTON LEE LAMB[k]

[a] *Cemagref, Lyon, France*
[b] *Electricité de France, Paris, France*
[c] *U.S. Forest Service, Fort Collins, CO, USA*
[d] *R2 Resource Consultants, USA*
[e] *U.S. Geological Survey, Bozeman, MT, USA*
[f] *U.S. Fish and Wildlife Service, Sacramento, CA, USA*
[g] *Freshwater Institute, Winnipeg, MB, Canada*
[h] *ENTRIX Environmental Consultants, Atlanta, GA, USA*
[i] *Colorado State University, Fort Collins, CO, USA*
[j] *Miller Ecological Consultants, Inc., Fort Collins, CO, USA*
[k] *U.S. Geological Survey, Fort Collins, CO, USA*

ABSTRACT

The conclusions of numerous stream restoration assessments all around the world are extremely clear and convergent: there has been insufficient appropriate monitoring to improve general knowledge and expertise. In the specialized field of instream flow alterations, we consider that there are several opportunities comparable to full-size experiments. Hundreds of water management decisions related to instream flow releases have been made by government agencies, native peoples, and non-governmental organizations around the world. These decisions are based on different methods and assumptions and many flow regimes have been adopted by formal or informal rules and regulations. Although, there have been significant advances in analytical capabilities, there has been very little validation monitoring of actual outcomes or research related to the response of aquatic dependent species to new flow regimes. In order to be able to detect these kinds of responses and to better guide decision, a general design template is proposed. The main steps of this template are described and discussed, in terms of objectives, hypotheses, variables, time scale, data management, and information, in the spirit of adaptive management. The adoption of such a framework is not always easy, due to differing interests of actors for the results, regarding the duration of monitoring, nature of funding and differential timetables between facilities managers and technicians. Nevertheless, implementation of such a framework could help researchers and practitioners to coordinate and federate their efforts to improve the general knowledge of the links between the habitat dynamics and biological aquatic responses. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: habitat modelling; hydropower; relicensing; monitoring; environmental flows; biological responses; Phabsim/IFIM; science-based management; long-term datasets

Received 18 August 2006; Revised 12 July 2007; Accepted 29 August 2007

INTRODUCTION

Hundreds of water management decisions related to instream flow releases (i.e. environmental flows) are presently being made by government agencies and non-governmental organizations around the world. The overwhelming majority of decisions for establishing environmental flows have been based on physical habitat needs for fish (Osborn and Allman, 1976; Stalnaker and Arnette, 1976), and have been modeled using the Physical Habitat Simulation System (PHABSIM; see Lamb *et al*., 2004b) developed by the U.S. Fish and Wildlife Service in the 1970s (Bovee, 1982; Annear *et al*., 2002). Although many new flow regimes have been adopted by formal or

*Correspondence to: Yves Souchon, Cemagref, Quantitative Hydroecology Laboratory CP 220, 69336 Lyon, Cedex 09, France.
E-mail: yves.souchon@cemagref.fr

informal rules and regulations, there have been few long term (i.e. greater than 2–3 years) monitoring studies designed to detect the response of aquatic species to these new flows (MacDonnell *et al*., 1989; Travnichek and Maceina, 1994; Travnichek *et al*., 1995; Propst *et al*., 2000; Vinson, 2001).

Monitoring has been primarily focused on verification of flow regime implementation (i.e. compliance monitoring) rather than on understanding the responses of target resources to changes in flow (i.e. validation monitoring; Propst and Gido, 2004; Miller, 2006). There are few cases in which there has been testing of the linkages between habitat alteration due to flow changes and responses in populations. As a result, it is difficult to improve existing analytical methods to better forecast healthy riverine ecosystems and changes in the population characteristics of target organisms.

In the past decade, there has been a conceptual leap as practitioners moved from the ‘minimum flow’ concept to system based flow regimes (Lamb *et al*., 2004a) such as nature-mimicking approaches (Katopodis, 1995; 2005), holistic methods (Tharme, 2003), or mimicking natural hydrographs (Poff *et al*., 1997; Richter *et al*., 1998). These broader approaches attempt to address the physical and biological processes necessary to maintain or restore riverine ecosystems and include flow scenarios to support native riparian communities, restore native fishes and invertebrate communities, integrate flow scenarios for white water recreation, and provide sufficient volume and timing of water to maintain physical processes. Although research is producing innovative approaches for defining environmental flows (Richter *et al*., 2003), scientifically based monitoring to verify effectiveness is generally lacking. In addition, opportunities are being missed to learn from numerous and diverse flow management decisions because few have been implementing adaptive management practices that are amenable to scientific experimentation (Poff *et al*., 2003). Petts *et al*. (2006) noticed that the lack of appropriate data (long term, coupled/biotic–abiotic) is a major obstacle to the development of new tools and especially integrated models. These limitations have led government agencies and industries in many countries to implement more scientifically valid monitoring programs.

Because of this interest, we believe a general design template is needed for studies to detect biological responses to new flow regimes over long time periods. Essential to this approach would be a central repository of information to facilitate improved communication and understanding of biological responses to different flow regimes. The result should be more certainty in decision making through better understanding of the responses of target organisms to flow regulation and project operations, more efficient use of resources, and reduced administrative costs. A general template for scientific monitoring should also enhance the acceptability and validity of results.

We suggest a template to design flow monitoring programs. Our approach should stimulate and guide multi-level research that will lead to improved assessment methods for detecting biological responses to flow management decisions.

APPROACH

Scientific monitoring programs should provide the means to measure the success or failure of changes in flow regimes. Well designed monitoring plans have clear objectives tied to specific questions of interest; clearly defined, replicable methods; clearly designed analysis pathways tied to the questions of interest; and incorporate adaptive management with a feedback loop to respond to new information and change the conditions to promote improvements and further learning (Figure 1). Monitoring programs typically fail when only one of these steps is missing. Failure is particularly likely when the goals of the monitoring plan are not clearly articulated.

There are a variety of monitoring types that can be applied for evaluating changes in flow regime. These include implementation and compliance monitoring, effectiveness monitoring, and validation monitoring (MacDonald *et al*., 1991). Implementation and compliance monitoring may be employed for determining whether flow releases specified for a given project were implemented as planned. Effectiveness monitoring specifies an outcome from an action. For example, was a change in flow regime responsible for changing a certain population or habitat condition over time? The number of interactions in this situation may be complex because many factors can influence the outcome. This type of monitoring may involve the development of conceptual models to identify pathways and linkages. An effectiveness monitoring plan will typically distill these linkages into key questions that can be used to design a monitoring study.

DOI: 10.1002/rra

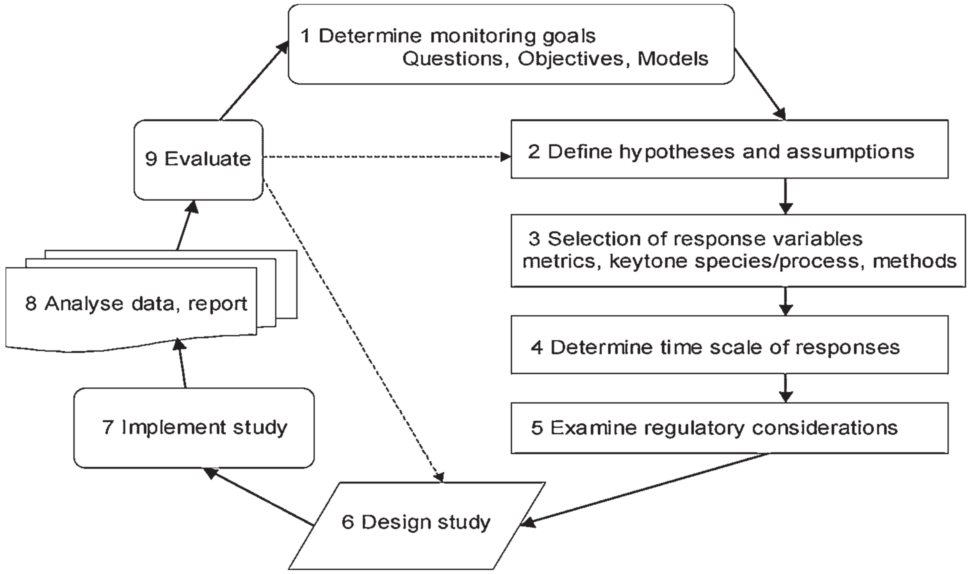

Figure 1. Flow chart of the general framework for an efficient long-term monitoring

Validation monitoring may also be appropriate in a post-flow change study. Validation monitoring is used to test assumptions about ecological relationships that are implicit in effectiveness monitoring. For example, large woody debris was once thought to be an impediment to migration and was often removed to create better fish habitat (Sedell *et al*., 1988). More recent work has emphasized the functions of large woody debris as rearing habitat and sediment storage. Validation monitoring helps us understand how aquatic systems work. Effectiveness and validation monitoring can help evaluate adaptive management prescriptions (Kershner, 1997).

DESIGNING A MONITORING TEMPLATE

Step 1: Determine monitoring goals and define questions of interest and project objectives

As an initial step, it is important to outline explicit assumptions relating to the project to be sure they are complete. For example, simply assuming that more flow results in better habitat may not be wise. Developing a conceptual model that shows explicit linkages among physical and biological processes is an important step in showing the relationships that will be tested. It is essential to define what is believed to be driving the process and describe the mechanisms that connect changes in flow to change in biological processes.

Available models may include predictions of flow–habitat relationships and conceptual models of how a stream system works. If either type of validated model is available, it is important to use these models to define study objectives: different scenarios should predict different potential increases of habitat or of a biological metric (change of fish biomass, change of the proportion of guilds). For example, positive relationships have been observed between fish population size (primarily salmonids) and habitat under limiting flow conditions (generally low summer flow), when such populations are at carrying capacity and have been relatively stable over a 3–4 year period (i.e. no major climatic event; Souchon and Capra, 2004). In the Rhône River rehabilitation effort, the public goal was to recover a ‘healthy and running’ river. These qualitative criteria were translated into quantitative hydraulic metrics linked to the ecological characteristics of the fish assemblages (Lamouroux *et al*., 1999; Souchon, 2004; Lamouroux *et al*., 2006). River restoration and habitat replacement offer an example of why it is important to carefully consider underlying assumptions. Restoration and habitat replacement are often considered as substitutes for increased flow.

Step 2: Hypotheses and assumptions

General hypotheses, such as ‘Increased flows will result in increased fish populations,’ are not very useful because it is almost impossible to determine why such hypotheses are incorrect. There may be many reasons why

DOI: 10.1002/rra

the hypothesis was rejected, such as: (1) the predicted response was too small to detect (i.e. the signal was swamped by other factors); (2) physical habitat was not limiting; and (3) the habitat criteria were wrong.

In contrast, hypotheses that test linkages between variables provide the opportunity to improve future assessment of instream flows. Specifying assumptions is the first step in determining why a hypothesis was rejected—for example, because an assumption was violated.[1]

Sample Hypothesis: Increased spawning habitat results in a decrease in redd superimposition.

Assumptions:

(1) Increased spawning habitat is not cancelled out by an increase in number of spawners;
(2) There are enough spawners originally to have redd superimposition;
(3) The spawning Habitat Suitability Index (HSI) is correct (the change in flow does increase the availability of spawning habitat).

Changes in key physical and biological parameters may be influenced by a variety of factors. If these factors are mainly dependent on flow manipulation, then developing a biologically meaningful flow regime may be possible. However, if the changes are due to multiple stressors on the entire watershed (e.g. diffuse pollution, excessive erosion and transport and downstream barriers) the chance of influencing biological communities by only manipulating flows is small. Identification of the limiting factors is useful to avoid this pitfall. The success of biological recovery depends on the degree of current impairment, if there are significant differences between the present and the enhanced situation in terms of increased minimum habitat, and restored physical functions (e.g. clean substrate for healthy spawning areas and invertebrate life). Recovery possibilities also depend on the ability of biota to reoccupy habitat. For example, adult insects may re-colonize by air and fish may move downstream or upstream if there are no physical barriers. The existence of healthy tributaries is essential as they can serve as biological reservoirs for missing species to re-colonize the improved riverine reach. Some of these species serve as critical links to other species completing their life histories. For example, many mussels require specific fish hosts to complete their life cycle. During appropriate seasons there must be immediate contact between the specific species of fish and the mussel reproductive stage (glochidia) in an area of suitable mussel habitat for successful attachment and encystment. Later, the larval mussels must drop onto a suitable habitat for survival and settlement. Providing or monitoring only adult mussel habitat would not be successful in expanding mussel populations if sufficient populations of the host species and their requirements are not also met. One of these examples is the pearl mussel, *Margaritifera margaritifera*, which needs salmonid as host (Skinner *et al*., 2003).

Step 3: Selection of response variables, metrics, keystone species and methods

Decision variables. The study design must provide for isolation of treatment effects (changed flow regime) from other sources of variation and allow assessment of the response of target resources (fish, amphibians, riparian vegetation) to the treatment (Kershner, 1997). For example, researchers should not attempt to detect a change in catchable trout with a different flow regime at the same time that catchable trout are being stocked. When too many variables are changed, there will be too much 'noise' to establish critical linkages of the biological response to the changed flow regime. There are many cases where a dam operator is required to implement a new flow regime along with other mitigation that could include habitat improvement via importing a missing sediment component and /or reintroduction of an extirpated species. It is essential to produce basic physical measurements that can be used to establish habitat–biotic relationships or provide better input to different models. Likewise, a suitable 'reference' condition must be specified. Such a situation has arisen in the relicensing of the Tapoco Project in Tennessee (Dilts *et al*., 2005). The settlement agreement and new Federal Energy Regulatory Commission (FERC) license require multi-year monitoring of habitat and biological change, but also require addition of gravel for habitat enhancement, high flows for white water boating, and possible stocking of endemic species. Clearly these measures must be phased to avoid confounding responses.

Selection of keystone habitats, species, guilds and processes. Selection of habitat and biological response variables is one of the most important elements to a successful monitoring program. Examples of biological

[1]As a practical matter, restricting the number of interactions among multiple variables to as few as possible is a wise practice because simpler relationships may be easier to test and the results will be easier to understand. Models can help guide decisions about which variables to control.

DOI: 10.1002/rra

response variables at different levels include indices of fish community integrity (Karr and Chu, 2000), guilds or morphological groupings (Travnichek *et al*., 1995; Leonard and Orth, 1988; Chan, 2001), populations of fish or other aquatic species (Studley *et al*., 1995; Sabaton *et al*., 2008), threatened or endangered species, or individual and population level indices such as growth, reproductive success recruitment to a certain age class (Nislow *et al*., 2004). In all cases the selection should be driven by the project objectives established by the biological purpose of the flow management change and the hypothesized biological response.

Spatially explicit habitat measurements are necessary to establish the mechanistic relationship to biological response. The scale at which the habitat is measured should coincide with the habitat needs of the species or life stage and should be consistent with the conceptual framework and models used to develop hypotheses. Examples of different levels of physical habitat that have been used with some success in the evaluation of biological responses include mesohabitat (Parasiewicz, 2001), microhabitat (Gallagher and Gard, 1999), and selected eco-hydraulic measures (shear stress; spawning habitat for invertebrates and mussels; Statzner and Higler, 1986; Statzner *et al*., 1988; Gore *et al*., 1994; Chan, 2001) feeding and foraging stations (Nislow *et al*., 2004). These and other studies have shown that scale is critical for understanding flow–habitat linkages. For example, pools, riffles and runs may be too gross to address the habitat needs and use by riffle dwelling species, but may be the right level for understanding biological response at the guild or community level.

Selection of methods. In all cases it is essential to produce basic physical measurements that can be used to establish habitat–biotic relationships or provide better input into different models. The longitudinal stratification of the study sites must be appropriate. The control should be upstream of the dam or on a comparable tributary (i.e. reference site), and experimental sites along the stream or river should be representative of the major morphological and hydrological longitudinal changes. Experimental and control reaches should be as similar as one can reasonably determine by direct measurement or validation of attributes (hydrology, geomorphology).

Depending on the goal of the study, there are a large range of tools from spatially explicit habitat measurements to methods that simplify the hydraulic and habitat characteristics. Examples might include for example IFIM/Phabsim in USA (Bovee, 1982; Bovee *et al*., 1998), Rhyhabsim in New Zealand (Jowett, 1989), Evha in France (Ginot *et al*., 1998) or generalized habitat models that offer the ability to simplify field data collection (see Estimhab in Lamouroux and Capra, 2002; Lamouroux and Souchon, 2002; Lamouroux and Jowett, 2005; Rosenfeld *et al*., 2007). Guilds of species whose habitat requirements are similar may provide an opportunity to evaluate habitat requirements where precise habitat models are not yet described (Leonard and Orth, 1988; Aadland *et al*., 1991; Travnichek *et al*., 1995). In all cases, before modeling it is important to question the relevance of the biological models (Scott and Shirvell, 1987; Orth, 1987; Holm *et al*., 2001; Kemp *et al*., 2003).

Biological monitoring methods must recognize and encompass the physical variables being studied. Synthesis of biological responses to physical changes requires a well-designed study plan that can isolate the cause and effect between physical change and biological response. The ability to determine sample sizes needed to detect change at the specified level (e.g. 10, 25%) should be part of the study design. An explicit statement of assumptions with the sampling technique can identify factors that impact results. For example, population estimators assume a closed population. While this may be true at the time of a single estimate, it may not be true for long-term monitoring. Identifying sources and sinks for populations can help refine the biological sampling design. Conceptual ecosystem or population models are a good method to begin identifying the variables.

Development of models. To understand the impact of all the involved factors at the scale of an entire population, a thorough analysis of the population dynamics (biotic relationship, ‘history’ of the population, impact of environmental parameters fluctuations) is required. For this, a Population Dynamics Model, based on a Leslie Matrix has been developed in France (Sabaton *et al*., 1997; Capra *et al*., 2003). This kind of model may be difficult to use, but can help simulate the evolution of a population over a long time scale. Simplified and generalized models could help to facilitate the application of habitat models at large scale and on multiple sites. For example, the addition of a simplified habitat description to some existing valuable biological long-term dataset could be one of the ways to quickly synthesize some relationships between physical habitat and biology.

DOI: 10.1002/rra

Step 4: Determining time scale of response

Time scale of response. The ability to reach conclusions with widely variable biological responses requires monitoring over a long duration. For example, monitoring of habitat restoration and salmonid response to habitat restoration in Fish Creek, Oregon for 7 years did not yield a statistically significant response in fish numbers (Reeves *et al*., 1990). A French experiment on 5 streams and 17 sites was based on 7 years of monitoring following an increase of the minimum instream flow (Sabaton *et al*., 2004, 2008). The results showed that 4 years was not enough time to point out significant positive change in the fish populations. Hydrological events like major floods, and also time for population rebuilding could explain these results. A dynamic population model, taking into account these abiotic and biotic variables is of great help to understand the observed trends (Gouraud *et al*., 2004).

An endangered species recovery effort on the San Juan River, New Mexico, US includes an ongoing monitoring effort of physical, biological and water quality data (Propst *et al*., 2000). The key native species are long lived (i.e. 25–50 year life spans) and require intensive long-term sampling to detect change. Species life spans should be a consideration in the study design to have realistic expectations on when a change could be detected. For example, short-lived species with high recruitment from young to adult may be more suited as a target species to detect short-term response to change while a long-lived species is better suited to be the target species for long-term ecological monitoring.

Step 5: Regulatory considerations

Regulatory requirements. Changes in regulations affect how the flow regime must be monitored. For example, the French Fishing Law (1984) followed by the Water Law (1992) imposed new constraints with respect to bypassed sections downstream of hydropower plants, setting a minimum value for the guaranteed flow for all hydroelectric facilities of 1/40th of the mean annual flow, and at least 1/10th of the mean annual flow at the relicensing. According to these laws, a discharge must ‘at all times, guarantee the survival, circulation and reproduction of the species living in the river before construction of the installation.’ In 1984 the instream flows downstream from about 400 hydropower plants were increased to the required value of 1/40th of the mean annual flow. One by one, the minimum flow has increased as each license is renewed (about 50 sites in 2004).

In the United States, the Federal Energy Regulatory Commission (FERC) issues and administers hydroelectric licenses. Many of the new licenses issued by the FERC since the early 90s have included improved flow conditions. Unlike France, the periodic relicensing of individual hydroelectric projects in the United States constitutes both a great challenge and an opportunity for monitoring. Every 30–50 years, each hydroelectric project must undergo a 5–10-year process called relicensing. This process involves multidisciplinary studies, public and stakeholder involvement, negotiations, mandatory conditioning by certain federal agencies. The result is a FERC mediated or negotiated change in project operations, often affecting many or all aspects of riverine flow management.

The conditions of the new FERC license though have rarely required much beyond compliance monitoring conditions, though in recent years more rigorous monitoring plans and effectiveness monitoring have been embodied into licenses as a result of settlement agreements reached and submitted to the FERC with the license application. It is also true that studies done before and during the relicensing process are often not done with attention to the types of post-license monitoring that may be required, so the studies are frequently not suitable as baseline data and cannot adequately guide decision-making (Lamb *et al*., 2001). Though there are some exceptions, this situation more frequently results in few lessons learned from past relicensing and flow management decisions and little gained knowledge to apply to the next one (Armour, 1991).

Limiting factors constraints. The French experiment pointed out several limiting factors affecting trout populations (Sabaton *et al*., 2004; 2008). The first factor was the effect of floods. In addition to some unusual and important floods, normal annual spring floods during the emergence period definitively masked the real impact of increases in flow. A poor quality substrate can also impact reproduction (due to lack of good spawning areas) and ultimately the population. The impact of adverse spawning conditions can be accentuated if the by-passed section is isolated (no tributaries, no exchange between upstream or downstream). This was clearly pointed out on some sites where the trout population was bolstered when overflow at the dam during important floods allowed young trout to enter the by-passed section. Fishing pressure can also be a limiting factor.

DOI: 10.1002/rra

Floods were also an important limiting factor in Martis Creek, California, where the timing of the floods (fall versus spring) determined whether brown or rainbow trout were the dominant species in the system (Strange *et al*., 1993). Floods in the fall resulted in vastly reduced recruitment of brown trout due to redd scour, and consequently rainbow trout becoming the dominant species in the system. In contrast, brown trout became dominant after spring floods scoured rainbow trout redds.

A prolonged drought in the late 1990s through 2003 in the San Juan River basin precluded obtaining specified flows due to lack of precipitation and runoff. The recommended flows for the San Juan were developed to mimic a snow-melt runoff hydrograph (Holden, 1999); however, lack of snow pack severely reduced the peak flows for several years. This lack of runoff was concurrent with the initiation of a monitoring program to evaluate the recommended flows. When the monitoring program was conducted, however, the conditions that were being monitored were much different than anticipated (Miller, 2006).

Step 6: Study design

Detecting flow-related biological changes to fish populations over time requires more than simply monitoring fish populations pre- and post-flow regulation. Investigations attempting to detect trends or evaluate the effects of a given flow operational condition on aquatic ecosystems (including fish) are inherently plagued with the difficulty of trying to account for and differentiate between continuous response signals, i.e. those that have and are influencing the biota at all times (e.g. climate, morphology, water quality, hydrology; see Ralph and Poole (2002) for the concept of hierarchical monitoring), and those of the specific operational condition or test factor (e.g. flow regulation scenario). Careful planning both in study design formulation as well as in selection of the most appropriate statistical tests for hypotheses testing is required. Clearly, a multidisciplinary approach involving statisticians, fish biologists, aquatic ecologists, hydrologists, and others is often warranted.

Many factors can affect the design of a particular study including: the type and variability of response variables on which data are collected; the potential size of the treatment effect; the ability to sample target organisms; the number of replicate samples collected; and the amount of money available for the study. Of these items, only a few are under the practitioner's control. The approach to study design should take each of these factors into account and adjust where possible to ensure that the questions of interest can be addressed.

There is a distinction between survey and experimental study designs. Because of the lack of replication, surveys are generally only used to make correlative statements about dependent and independent variables, whereas field experiments that employ replication can be used to investigate causation by keeping particular factors constant while varying others.

The analysis phase is as important as the data collection. Often the expertise necessary to answer the questions that have been developed is not locally available. If the study is to go on over decades, it is necessary to plan for technology upgrades but set protocols such that data will be comparable. Peer review of a study design is highly recommended.

Statistics. Fundamentally, a statistical analysis of a hypothetical impact seeks to identify whether changes in the response variable are due to the impact or random chance. The success of the statistical analysis rests on several components: the natural variability in the response variable, the size of the impact, the number of samples, and the statistical test. Statistical analysis may be performed on univariate (e.g. total density) or multivariate (e.g. matrix of species specific densities) data. Depending on whether the response variable is univariate or multivariate, particular statistical tests and techniques have been used for fish data (see Roni *et al*., 2002 for more detailed advices).

Step 7: Implement study

Many monitoring studies will require data collection over long time periods (MacDonald *et al*., 1991; Kershner *et al*., 2004). The long time frames are necessary to account for changing environmental conditions, obtaining replicate samples, allowing sufficient time for the target aquatic resource to respond and for making adjustments in sampling protocol based on intermediate results.

After a study design is defined, the identification of field sites and the selection of appropriate field methods are necessary. The general guidelines for field sample sites should be identified in the methods, but specific selection criteria may have to be modified by local environmental conditions. It is important to document the location of field

DOI: 10.1002/rra

sites with photos and geo-referenced points for subsequent site visits. Establishing these permanent sites can reduce variability associated with re-sampling and reduce the number of sites necessary for change detection (Roper *et al*., 2003). Detailed cross-sections or other survey methods such as spatially explicit habitat mapping may be necessary to document physical habitat changes (Harrelson *et al*., 1994). Importantly, the study sites chosen should be varied enough so that the main phenomena linked to expected limiting factors can be studied. It is of course important to try to reduce the number of limiting factors at a given site. Knowing the real state of the population before changing the instream flow is not easy. The period during which the population should be monitored before the change in flow must be long enough to be able to take into account the natural inter-annual fluctuations of the fish densities. And then, the time of experiment after the change in flow must be long enough to assess any actual population changes linked to this change in flow.

In Fish Creek, Oregon, researchers were not able to detect a statistically significant change in fish numbers due to habitat improvement in 7 years of study (Reeves *et al*., 1997). In such situations, a qualitative response (e.g. increasing trend) might be more appropriate than a quantitative one that results in an indicator of statistical significance. The important point is to incorporate a response metric that is mechanistically linked to the experimental manipulation. If the response variables can be mechanistically related to the manipulation, it may be possible to extend the inferences to other systems where the same stress–response mechanisms occur.

The methods chosen should be measurable and repeatable. Consistency in data collection is often overlooked and can cause difficulty in comparing data and interpreting results. Training and the use of experienced field staff are important for quality control and quality assurance (Archer *et al*., 2004). Our collective experience is that critical components of implementing data collection include: safety training, practice in the use of the equipment and methods, experience and crew composition. Rigid adherence to standard methods and quality control studies conducted with field technicians helps investigators identify sampling problems early and refine methods (Roper *et al*., 2002; Archer *et al*., 2004). One of the most significant problems with long-term monitoring studies is when field methods change during the sampling period. Different methods that attempt to quantify the same metric often are not comparable (Whitacre *et al*., 2007).

Possibly the best examples of the application of the principles outlined in this paper are the works of Travnichek and Maceina (1994); Bain *et al*. (1988); Bowen (1998) on the response of warm water fish communities to changes in flow management of the Tallapoosa River (MAD: 133 $m^3 s^{-1}$) downstream of Thurlow Dam, USA. The process followed in this work included the development of a conceptual model, key questions and hypotheses (Bain and Boltz, 1989); use of reference (control) streams; careful selection of response metrics, measurement methods and scales (Bain and Finn, 1982; 1988; Bain *et al*., 1988). The monitoring effort employed a good study design, effectiveness and validation monitoring, pre- and post-change monitoring, and long-term implementation. Within 5–7 years, this work yielded valuable findings about the response of warm water fish community to the initiation of a minimum-flow release downstream from a hydroelectric dam (Travnichek and Maceina, 1994; Travnichek *et al*., 1995; Bowen, 1998). The monitoring and related analyses continued to yield valuable information and revised hypotheses for further investigation of changes in flow regulation patterns (Bowen *et al*., 1998). Another such example is presented for the Rhône River (MAD: 1000 $m^3 s^{-1}$), below Pierre-Bénite dam (Lamouroux *et al*., 2006).

Step 8: Data analysis and reporting

A crucial element that often gets overlooked is the analysis and dissemination of information. Systematic reporting is necessary. Reports should evaluate the original study objectives; provide periodic updates to interested parties; and promote peer review. One common failing of many monitoring projects is not actively analysing and reporting interim data. Support for monitoring tends to be high during the early stages, but wanes as time passes. Annual meetings and presentation of information to interested public and agency managers help to ensure support for the continuation of monitoring.

In instances where physical and biological data are being monitored, it is advisable to conduct a pre-test of datasets to ensure compatibility during the analysis. This is particularly important in studies with multiple disciplines using different study metrics. For example, fish census or abundance data can be collected by density (number per unit area) or effort (number per unit time) and may not be directly comparable. A pre-test of the analysis sequence can help to correct incompatible datasets early in the study.

DOI: 10.1002/rra

Data compilation and analysis should provide a variety of interpretive techniques from very simple to more complex, depending on the questions. Often descriptive statistics accompanied by visual displays of the analysis (frequency distributions, pie charts, graphs) are powerful ways to display differences to managers and the lay public. Simulation models that show consequences of various flow regimes to habitat are also useful ways to display data especially when patterns may not be obvious.

Although thousands of flow diversion projects exist throughout the world, we know of only a handful of population response studies that have attempted to evaluate change over time. One such study was conducted by Studley *et al*. (1995) on the Tule River in California. The study involved the monitoring of fish and benthic macroinvertebrate communities, as well as water temperatures over a 10 year period at study sites located both above and below flow diversion points. Another example is the San Juan River Basin Recovery Implementation Program (SJRIP) in the United States. That program includes a monitoring plan and protocol to assess impact of flow and management recommendations on the recovery of two endangered species. The SJRIP monitoring program includes the development of monitoring protocols; analysis, data synthesis and peer review (Propst *et al*., 2000). Results of the monitoring are reported annually with detailed data synthesis at specified intervals. Monitoring protocols are modified to correct incompatibility, address data gaps or new hypothesis.

Publication of monitoring findings in the peer-reviewed literature should be encouraged. Collaboration techniques, assumptions, interpretations, judgments, and data compilation procedures should all be documented. The publication of methods and findings provides validation or cause rejection of the original hypotheses; shares data; provides information on the effects of changing flow releases; and suggest new ideas or approaches as a result of the findings. Data archiving and sharing through the Internet provides the public and other scientists with instant access.

Step 9: Management implications – adaptive management

There is tremendous benefit from incorporating adaptive management into study designs and management operations because the ability to re-assess and make changes while a project is on-going adds to the likelihood of success. The results of monitoring can be used to modify management plans when better data are available. Adaptive management is an approach to natural resource policy based on the assumption that policies (i.e. flow regulations) can be experiments from which policy makers, scientists and the public can learn (Walters and Holling, 1990; Lee, 1993). Adaptive management provides a direct feedback loop between science and management so that management and policy decisions can be modified based on new information. If possible, identify response variables that will show response before subsequent changes are made. If there is the possibility of catastrophic response, every attempt should be made to reverse the change if/when that response is detected. It is also beneficial to have the flexibility to change if an expected/needed response is not evident after the expected time period. Adaptive management allows flexibility and enables learning. Van Winkle *et al*. (1997) provide important precautionary principles for the application of adaptive management for flow regulation.

RECOMMENDATIONS AND CONCLUSIONS

One of the primary objectives of this paper is to encourage researchers and practitioners to adopt a broader monitoring framework. The foremost need is to focus data collection on obtaining information on the biological effects of site-specific water management decisions. However, such data collection efforts can be set up so that the results are transferable. To capitalize on potential learning opportunities from diverse projects and the responses of the affected species, there needs to be a coordinated effort among researchers and practitioners to develop protocols, define objectives and list potential candidate sites. Researchers experienced in analyzing effects of flow scenarios and biological response should be called upon to develop study design templates that others can adapt. Common templates for study design and the selected variables to measure will facilitate comparisons and provide a large sample from which to apply results to future cases.

We recommend the following actions:

(1) Develop a network of researchers and practitioners to prioritize information needs, establish case and site selection criteria, develop study standards and templates and establish a candidate list of projects for long-term monitoring;

DOI: 10.1002/rra

(2) Identify the best opportunities (locations, water projects) for long-term monitoring and collaborate and focus funding to produce fewer but more complete and rigorous monitoring programs;
(3) Design monitoring programs that incorporate rigorous techniques with clearly defined objectives and methods tied to specific questions of interest;
(4) Shift monitoring efforts from 'measuring change (e.g. we found more fish)' to 'measuring and understanding change (e.g. the fish population responded due to these factors)';
(5) Scale monitoring to the site-specific case but follow rigorous data collection protocols and study designs that test hypotheses, answer specific questions and provide for extrapolation to similar systems for similar or the same species;
(6) Establish a formal repository of information and publications;
(7) Communicate through peer reviewed journals, formal and informal networks, and regularly scheduled meetings;
(8) Work with potential funding sources (government and non-government) to support a targeted research agenda; new long-term funding approaches are emerging in the field of river restoration (see experience of the Bonneville Environmental Foundation, in the US Pacific Northwest, Reeve *et al*., 2006)
(9) Coordinate with academia to recruit interested students to further the long-term research interests.

The adoption of such a framework is not always easy, due to differing interests of actors, regarding the duration of monitoring, nature of funding and differential timetables between facilities managers and researchers.

Recent large compilations of stream restoration case studies (Alexander and Allan, 2006) reveal the need to, intensify monitoring, improve its quality, and implement it at a larger scale than currently. Considering flow alterations as ecosystem manipulation, better design, hypotheses definition and testing, with attributes developed in that paper, has the potential to improve the situation. Comparing the predictions of *a priori* hypotheses (Yoccoz *et al*., 2001) with measurements of variables derived from monitoring data, before and after the manipulation, could be used to infer the mechanistics relationships between physical determinants and aquatic biota responses.

Added to the general awareness, the legal context could also help to build new opportunities. EU Framework Water Directive has instigated the state members to evaluate the ecological status of streams and rivers by a reinforced monitoring. Some of the future operational monitoring are analogous to our validation monitoring definition.

We plea that the results of these monitoring efforts will not only be used for reporting, but also must be synthesized across studies to allow generalizations.

Our recommendation is simply that future monitoring, by proper design, will allow for a better understanding of the driving forces of changes in biological diversity and the basis of progress for a better management of the hydrosystems.

ACKNOWLEDGEMENTS

This paper was inspired by discussions held at a workshop on shared experiences on flow alterations and biological monitoring. This workshop was held at the US Geological Survey, Fort Collins, Colorado, USA on 22 to 24 March 2005. It was sponsored by USGS and USDA. The authors thank all participants for the fruitful brainstorming: Ken Bovee, Zack Bowen, Robert Milhous, Terry Waddle, Katie Wundrock, Steve Railsback. The rough draft was compiled by Eve Shauer. D. Gilvear reviewed the final version of the manuscript and helped to improve it. Ton Snelder gave linguistic advices on the final corrections.

REFERENCES

Aadland LP, Cook CM, Negus MT, Drewes HG, Anderson CS. 1991. *Microhabitat preferences of selected stream fishes and a community-oriented approach to instream flow assessments. Investigational Report, Minnesota Department of Natural Resources, Section of Fisheries: St. Paul, MN; 125 p.*

Alexander GG, Allan JD. 2006. Stream restoration in the Upper Midwest, USA. *Restoration Ecology* **14**(4): 595–604.

DOI: 10.1002/rra

Annear TC, Chisholm I, Beecher H, Locke A, Aarrestad P, Burkhart N, Coomer C, Estes C, Hunt J, Jacobson R. 2002. *Instream flows for riverine resource stewardship. The Instream Flow Council: Cheyenne, WY, USA.*

Archer EK, Roper BB, Henderson RC, Kershner JL, Mellison SC. 2004. *Testing common stream sampling methods: how useful are these techniques for broad-scale, long-term monitoring? General Technical Report RMRS-GTR-122, USDA Forest Service, Rocky Mountain Research Station: Fort Collins, CO; 15 p.*

Armour CL, Taylor JG. 1991. Evaluation of the instream flow incremental methodology by U.S. Fish and Wildlife Service field users. *Fisheries* **16**: 36–43.

Bain MB, Boltz JM. 1989. *Regulated Sreamflow and Warmwater Stream Fish: General Hypothesis and Research Agenda. Biological Report 89, U.S. Fish and Wildlife Service: Washington, DC.*

Bain MB, Finn JT. 1982. An alternative approach to assessing habitat suitability for stream fish. In *An evaluation of methodologies for assessing the effects of flow fluctuation on stream fish, Bain MB (ed). U.S. Fish and Wildlife Service: Newton Corner, Massachusetts; 77–98.*

Bain MB, Finn JT, Booke HE. 1988. Streamflow regulation and fish community structure. *Ecology* **69**: 382–392. DOI:10.2307/1940436

Bovee KD. 1982. *A guide to stream habitat analysis using the Instream Flow Incremental Methodology. U.S.D.S. Fish and Wildlife Service. Office of Biological Services: Fort Collins, Colorado; 248 p.*

Bovee KD, Lamb BL, Bartholow JM, Stalnaker CB, Taylor J, Henriksen J. 1998. Stream habitat analysis using the instream flow incremental methodology. *Information and Technology Report*, U.S. Geological Survey, Biological Resources Division, 131 p.

Bowen ZH. 1998. Relations between fishes and habitat in the Tallapoosa River system. *Ph.D. dissertation*. Auburn University, Auburn, Alabama. 109 p.

Bowen ZH, Freeman MC, Bovee KD. 1998. Evaluation of generalized habitat criteria for assessing impacts of altered flow regimes on warmwater fishes. *Transactions of the American Fisheries Society* **127**: 455–468. DOI: 10.1577/1548-8659

Capra H, Sabaton C, Gouraud V, Souchon Y, Lim P. 2003. A population dynamics model and habitat simulation as a tool to predict brown trout demography in natural and bypassed stream reaches. *River Research and Applications* **19**: 551–568. DOI: 10.1002/rra.729

Chan MD. 2001. Fish ecomorphology: predicting habitat preferences of stream fishes from their body shape, *Philosophical Dissertation*, Blacksburg, University of Virginia: USA. 268 p. http://scholar.lib.vt.edu/theses/available/etd-05242001-183326/unrestricted/mattchan.pdf

Dilts E, Leonard P, Hill D. 2005. Development of an integrated flow regime recommendation for the Cheoah River, N.C. Proceedings of the 2005 Georgia Water Resources Conférence, April 25–27 2005. Hatcher KJ (ed). Institute of Ecology, The University of Georgia, Athens, Georgia. http://www.uga.edu/water/GWRC/Papers/DiltsE-GWRCpaper.pdf#search=%22Tapoco%20relicensing%20reference%22

Gallagher SP, Gard MF. 1999. Relationship between chinook salmon (Oncorhynchus tshawytscha) redd densities and PHABSIM-predicted habitat in the Merced and Lower American rivers, California. *Canadian Journal of Fisheries and Aquatic Sciences* **56**: 570–577.

Ginot V, Souchon Y, Capra H, Breil P, Valentin S. 1998. Logiciel EVHA 2.0. Evaluation de l'habitat physique des poissons en rivière, Cemagref BEA/LHQ et Ministère de l'Aménagement du Territoire et de l'Environnement: 82 p. http://www.lyon.cemagref.fr/bea/lhq/evha.shtml

Gore JA, Niemela S, Resh V, Statzner B. 1994. Near-substrate hydraulic conditions under artificial floods from peaking hydropower operation: a preliminary analysis of disturbance intensity and duration. *Regulated Rivers: Research and Management* **9**: 15–34.

Gouraud V, Sabaton C, Capra H. 2004. Role of habitat variability in trout populations dynamics: application of a dynamic population model to three french rivers. *Hydroécologie Appliquée* **14**: 221–244.

Harrelson CC, Rawlins CL, Potyondy JP. 1994. *Stream Channel Reference Sites: An Illustrated Guide to Field Technique. U.S. Department of Agriculture, Forest Service, Rocky mountain Forest and Range Experiment Station: Fort Collins 61 p.*

Holden PB. 1999. Flow recommendations for the San Juan River. *The San Juan River Basin Recovery Implementation Program. U.S. Fish and Wildlife Service: Albuquerque, New Mexico.*

Holm CF, Armstrong JD, Gilvear DJ. 2001. Investigating a major assumption of predictive instream habitat models: is water velocity preference of juvenile Atlantic salmon independent of discharge? *Journal of Fish Biology* **59**: 1653–1666.

Jowett IG. 1989. River hydraulic and habitat simulation, RHYHABSIM computer manual. *New Zealand Miscellaneous Report No. 49*.

Karr JR, Chu EW. 2000. Sustaining living rivers. *Hydrobiologia* **422**: 1–14. DOI:10.1023/A:1017097611303

Katopodis C. 1995. Stream restoration for North American fish species. In *River Front Symposium, Tokyo: Japan; 1–28.*

Katopodis C. 2005. Developing a toolkit for fish passage, ecological flow management and fish habitat works. *IAHR Journal of Hydraulic Research* **43**: 451–467.

Kemp PS, Gilvear DJ, Armstrong JD. 2003. Do juvenile Atlantic salmon parr track local changes in water velocity? *River Research and Applications* **19**: 569–575.

Kershner JL. 1997. Watershed restoration monitoring and adaptative management. In *Watershed Restoration: Principles and Practices, Williams JE, Dombeck MP, Wood CA (eds). American Fisheries Society: Bethesa, Maryland; 116–135.*

Kershner JL, Coles-Ritchie M, Cowley E, Henderson RC, Kratz K, Quimby C, Turner DM, Ulmer LC, Vinson MR. 2004. *Guide to Effective Monitoring of Aquatic and Riparian Resources. Department of Agriculture, Forest Service, Rocky Moutain Research station: Fort Collins, CO.*

Lamb BL, Burkardt N, Taylor JG. 2001. The importance of defining technical issues in inter-agency environmental negotiations. *Public Works Management & Policy* **5**: 220–232.

Lamb BL, Sabaton C, Souchon Y. 2004a. Use of the instream flow incremental methodology. Special issue. *Hydroécologie Appliquée* **14**: 1–270.

Lamb BL, Sabaton C, Souchon Y. 2004b. Use of the instream flow incremental methodology: introduction to the special issue. *Hydroécologie Appliquée* **14**: 1–7.

Lamouroux N, Capra H, Pouilly M, Souchon Y. 1999. Fish habitat preferences in large streams of southern France. *Freshwater Biology* **42**: 673–687. DOI: 10.1046/j.1365-2427.1999.00521.x

Lamouroux N, Jowett IG. 2005. Generalized instream habitat models. *Canadian Journal of Fisheries and Aquatic Sciences* **62**(1): 7-14.

Lamouroux N, Olivier JM, Capra H, Zylberblat M, Chandesris A, Roger P. 2006. Fish community changes after minimum flow increase: testing quantitative predictions in the Rhône River at Pierre-Bénite, France. *Freshwater Biology* **51**: 1730–1743. DOI: 10.1111/j.1365-2427.2006.01602.x

Lamouroux N, Souchon Y. 2002. Simple predictions of instream habitat model outputs for fish habitat guilds in large streams. *Freshwater Biology* **47**: 1531–1542. DOI: 10.1046/j.1365-2427.2002.00880.x

Lee KN. 1993. *Compass and Gyroscope. Island Press: Washington, DC, USA.*

Leonard PM, Orth DJ. 1988. Use of habitat guilds of fishes to determine instream flow requirements. *North American Journal of Fisheries Management* **8**: 399–409.

MacDonald LH, Smart AW, Wissmar RC. 1991. *Monitoring Guidelines to Evaluate Effects of Forestry Activities on Streams in the Pacific Northwest and Alaska, EPA 910/9-91-001. U.S. Environmental Protection Agency: Seattle, Washington; 156 p.*

MacDonnell L, Rice T, Shupe S. 1989. *Instream Flow Protection in the West. University of Colorado School of Law, Natural resources Law Center: Boulder, CO.*

Miller WJ. 2006. *San Juan River Standardized Monitoring Program, Five Year Integration Report. Final Report, The San Juan River basin recovery implementation program, Biology Committee and Researchers: Albuquerque, NM; 83 p.*

Nislow KH, Sepulveda AJ, Folt CL. 2004. Mechanistic linkage of hydrologic regime to summer growth of age-0 Atlantic salmon. *Transactions of the American Fisheries Society* **133**: 79–88. DOI: 10.1577/T02-168

Orth DJ. 1987. Ecological considerations in the development and application of instream flow-habitat models. *Regulated Rivers: Research and Management* **1**: 171–181.

Osborn JF, Allman CH. 1976. *Instream Flow Needs. Proceedings of the Symposium and Specialty Conference on Instream Flow Needs. American Fisheries Society: Bethesda, MD, USA.*

Parasiewicz P. 2001. MesoHABSIM: a concept for application of instream flow models in river restoration planning. *Fisheries* **26**: 6–13.

Petts GE, Nestler J, Kennedy R. 2006. Advancing science for water resources management. *Hydrobiologia* **565**: 277–288. 10.1007/s10750-005-1919-1

Poff LN, Allan JD, Palmer MA, Hart DD, Richter BD, Arthington AH, Rogers KH, Meyer JL, Stanford JA. 2003. River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment* **1**: 298–306.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. A paradigm for river conservation and restoration. *Bioscience* **47**: 769–784.

Propst DL, Gido KB. 2004. Responses of native and nonnative fishes to natural flow regime mimicry in the San Juan River. *Transactions of the American Fisheries Society* **133**: 922–931.

Propst DL, Platania SP, Ryden DW, Bliesner RL. 2000. *San Juan River monitoring plan and protocols. The San Juan River basin recovery implementation program, U.S. Fish and Wildlife Service: Albuquerque, NM.*

Ralph SC, Poole GC. 2002. Putting monitoring first: designing accountable ecosystem restoration and management plans, In *Restoration of Puget Sound rivers, Montgomery DR, Bolton S, Booth DB, Wall L (eds). University of Washington Press: Seattle; 226–245.*

Reeve T, Lichatowich J, Towey W, Duncan A. 2006. Building science and accountability into community-based restoration: can a new funding approach facilitate effective and accountable restoration? *Fisheries* **31**(1): 17–24.

Reeves GH, Everest FH, Sedell JR, Hohler DB. 1990. *Influence of Habitat Modifications on Habitat Composition and Anadromous Fish Populations in Fish Creek, Oregon 1983-88. U.S. Department of Energy, Bonneville Power Administration, Division of Fish and Wildlife: Portland, OR; 44 P.*

Reeves GH, Hohler DB, Hansen BE, Everest FH, Sedell JR, Hickman TL, Shively D. 1997. Fish habitat restoration and forestry practices in the Pacific Northwest: Fish Creek in Oregon. In *Watershed Restoration: Principles and Practices. Williams JE, Wood CA, Dombeck MP. American Fisheries Society: Bethesda, Maryland; Chapter 20: 335–359.*

Richter BD, Baumgartner JV, Braun DP, Powell J. 1998. A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research and Management* **14**: 329–340. DOI: 10.1002/(SICI)1099-1646

Richter BD, Mathews R, Harrison DL, Wigington R. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* **13**: 206–224.

Roper BB, Kershner JL, Archer E, Henderson R, Bouwes N. 2002. An evaluation of physical stream habitat attributes used to monitor streams. *Journal of the American Water Resources Association* **38**: 1637–1646.

Roper BB, Kershner JL, Henderson R. 2003. The value of using permanent sites when evaluating stream attributes at the reach scale. *Journal of Freshwater Ecology* **18**: 585–592.

Roni P, Liermann M, Steel A. 2002. Monitoring and evaluating fish response to instream restoration. In *Restoration of Puget Sound Rivers, Montgomery F DR , Bolton F S , Booth F DB , Wall F L (eds). University of Washington Press: Seattle; 319–339.*

Rosenfeld JS, Post J, Robins G, Hatfield T. 2007. Hydraulic geometry as a physical template for the River Continuum: application to optimal flows and longitudinal trends in salmonid habitat. *Canadian Journal of Fisheries and Aquatic Sciences* **64**(5): 755–767.

Sabaton C, Siegler L, Gouraud V, Baglinière JL, Manné S. 1997. Presentation and first applications of a dynamic population model for brown trout (*Salmo trutta*): aid to river management. *Fisheries Management and Ecology* **4**: 425–438.

Sabaton C, Souchon Y, Lascaux JM, Vandewalle F, Baran P, Baril B, Capra H, Gouraud V, Lauters F, Lim P. 2004. A French evaluation of microhabitat component of IFIM based on habitat and brown trout population monitoring. *Hydroécologie Appliquée* **14**: 245–270.

Sabaton C, Souchon Y, Capra H, Gouraud V, Lascaux JM, Tissot L. 2008. Long term brown trout populations responses to flow manipulation. 10th ISORS Conference.

Scott D, Shirvell CS. 1987. A critique of the instream flow incremental methodology and observations on flow determination in New Zealand in Regulated stream. In *Advances in Ecology, Craig JF, Kemper BJ (eds). Plenum press: New York; 27–43.*

Sedell JR, Bisson PA, Swanson FJ, Gregory SV. 1988. What we know about large trees that fall into streams and rivers. In *From the Forest to the Sea: A Story of Fallen Trees, Maser C, Tarrant RF, Trappe JM, Franklin JF (eds). General Technical Report PNW—GTR-229, Pacific Northwest Research Station, USDA Forest Service: Portland, Oregon; 47–81.*

Skinner A, Young M, Hastie L. 2003. *Ecology of the Freshwater PearlMussel. Conserving natura 2000, Rivers ecology, Series no. 2, English Nature: Peterborough.*

Souchon Y. 2004. Mediterranean case study: The Rhône river: hydromorphological and ecological rehabilitation of a heavely man-used hydrosystem. In *Assessment and Provision of Environmental flows in Mediterranean Watercourses: Basic Concepts, Methodologies and Emerging Practice, Office IUCNM (ed). Water and Nature Initiative; 3–11.*

Souchon Y, Capra H. 2004. Aquatic habitat modelling: biological validations of IFIM/Phabsim methodology and new perspectives. *Hydroécologie Appliquée* **14**: 9–25.

Stalnaker CB, Arnette JL. 1976. *Methodologies for Determining Stream Resource Flow Requirements: An Assessment. U.S. Fish and Wildlife Service: Washington, DC.*

Statzner B, Gore JA, Resh VH. 1988. Hydraulic stream ecology: observed patterns and potential applications. *Journal of the North American Benthological Society* **7**: 307–360.

Statzner B, Higler B. 1986. Stream hydraulics as a major determinant of benthic invertebrate zonation patterns. *Freshwater Biology* **16**: 127–139.

Strange EM, Moyle PB, Foin TC. 1993. Interactions between stochastic and deterministic processes in stream fish community assembly. *Environmental Biology of Fishes* **36**: 1–15.

Studley TK, Baldridge JE, Wise LM, Spina AP, Railsback SF, McElravy E, Travanti L, Yuen TDF, Lindahl RB, Chase SD, Smith RW. 1995. *Response of fish populations to altered flows project, Volume I: predicting trout populations from streamflow and habitat variables.* Research and Development Project, Pacific Gas and Electric Company, Entrix. Report n° 009.4-94.3

Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**: 397–441. DOI: 10.1002/rra.736

Travnichek VH, Bain MB, Maceina MJ. 1995. Recovery of a warmwater fish assemblage after the initiation of a minimum-flow release downstream from a hydroelectric dam. *Transactions of the American Fisheries Society* **124**: 836–844.

Travnichek VH, Maceina MJ. 1994. Comparison of flow regulation effects on fish assemblages in shallow and deep water habitats in the Tallapoosa River, Alabama. *Journal of Freshwater Ecology* **9**: 207–216.

Van Winkle W, Coutant CC, Jager HI, Mattice JS, Orth DJ, Otto RG, Railsback SF, Sale MJ. 1997. Uncertainty and instream flow standards: perspectives based on hydropower research and assessment. *Fisheries* **22**: 21–22.

Vinson MR. 2001. A history of aquatic macroinvertebrate assemblage changes downstream from a large dam. *Ecological Applications* **11**: 711–730.

Walters CJ, Holling CS. 1990. Large-scale management experiment and learning by doing. *Ecology* **71**(6): 2060–2068.

Whitacre HW, Roper BB, Kershner JL. 2007. A comparison of protocols and observer precision for measuring physical attributes of streams in Oregon and Idaho. *Journal of Water Resources Association* **43**(4): 923–937.

Yoccoz NG, Nichols JD, Boulinier T. 2001. Monitoring of biological diversity in space and time. *Trends in Ecology and Evolution* **16**: 446–453.